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A comparison of one-minute probability density distributions of global horizontal solar irradiance conditioned to the optical air mass and hourly averages in different climate zones

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Abstract

In this study, one-minute global horizontal solar irradiance distributions conditioned to the optical air mass, m, and hourly average of global horizontal solar irradiance were studied at sites in five different climate regions. For this purpose, the clearness index, k_t, which accounts for the atmospheric transmittance, has been used. These distributions are fitted by functions based on the Boltzmann statistic.

The one-minute distributions of k_t conditioned to m found are either unimodal or bimodal, depending on the location and the value of m. These distributions are different for each of the locations analyzed. The one-minute distributions of k_t conditioned to their hourly value (k_{th}) are unimodal, and are in turn different at each of the locations analyzed. The one-minute k_t distributions conditioned to both m and k_{th} analyzed are also unimodal. These distributions were found to be the same (Kolmogorov–Smirnov test, $p > 0.05$) at different sites in 5% of the cases compared, the majority of which show very cloudy sky conditions and decrease monotonically at clearer-sky conditions. These results point to the importance of local distribution and type of clouds in one-minute solar irradiance distributions, and highlight the role of local atmospheric clear sky transparency in differentiating these distributions.

Keywords: Solar energy; Optical air mass; High frequency solar radiation; Clearness index; Climate zones; Aerosol optical depth

1. Introduction

The design of systems for harnessing solar energy requires knowledge of the temporal evolution of solar radiation. The intermittent nature of instantaneous solar irradiance has a considerable impact on the nonlinear behaviour of solar energy conversion systems and its characterization is essential in establishing adequate operating strategies for solar power plants (Fernández-Peruchena et al., 2012; Gansler et al., 1995; Tovar et al., 1999). Thus, the knowledge of the statistical behaviour of short-term variability of solar irradiance will facilitate a more precise evaluation of the uncertainty in the long-term annual energy production of solar power plants (Fernández-Peruchena et al., 2014). This, in turn, will allow simulation of certain aspects of plant operation, such as transient effects, and the evaluation of energy management options (Gansler et al., 1995; Tovar et al., 1999, 2001; Fernández-Peruchena et al., 2010; Suehrcke and McCormick, 1988; Vijayakumar et al., 2005).

The use of hourly solar irradiance series excludes much sensitive information, such as that derived from the effects

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of clouds or from changes in the angular position of the Sun (Fig. 1), and can introduce erroneous estimation of the functioning of solar conversion systems characterized by a rapid nonlinear response to incident solar radiation (Fernández-Peruchena et al., 2014; Suehrcke and McCormick, 1988), especially photovoltaic systems (Mills and Wiser, 2010). To compare these estimates, the usability parameter, which quantifies the solar fraction of the radiation incident on the surface that exceeds a specified threshold or critical level (Vijayakumar et al., 2005), was applied. This parameter has been evaluated at several frequencies, and differences have been found between hourly and daily usability, and between hourly and instantaneous usability curves, showing that both daily and hourly values lead to a conservative estimate of usability (Vijayakumar et al., 2005; Suehrcke and McCormick, 1989). Likewise, a study by Walkenhorst et al. (2002) on the influence of the short-term dynamics of daylight on simulation-based predictions of the annual daylight availability in a building concluded that the use of hourly series of solar irradiance instead of one-minute series resulted in a 27% underestimation of artificial light demand in buildings.

Global Horizontal solar Irradiance (GHI) series have usually been studied as a function of the clearness index, k_t (the ratio of GHI to top-of-atmosphere solar irradiance on the same plane). Since the pioneering study done by Liu and Jordan (1960), in which probabilistic distributions for daily k_t were shown, several authors have examined the behaviour of solar irradiance series when time resolution is reduced from monthly (Bohlen and Schumacher, 1996; Fernández-Peruchena et al., 2014; Tiba and Fraidenraich, 2004) to daily (Aguiar et al., 1988; Amato, 1986; Bartoli, 1983; Brinkworth, 1977; Klein, 1978) and higher-frequency scales (Fernández-Peruchena et al., 2010, 2009; Aguiar and Collares-Pereira, 1992; Balouktsis and Tsalides, 1986;Goh and Tan, 1977; Graham and Hollands, 1990; Mora and Sidrach-de-Cardona, 1998; Mustacchi et al., 1979; Palomo, 1989). Five-minute intrahourly series of solar radiation has been studied at different locations (Assunçâo et al., 2003; Gonzalez and Calbo, 1999; Jurado et al., 1995). Suehrcke and McCormick (1988) and Gansler et al. (1995) compared cumulative frequency distributions of short-term solar radiation data to hourly data. Skartveit and Olseth (1992) developed a stochastic model for generating five-minute GHI values from the corresponding hourly averages based on data measured in Atlanta, Geneva and San Antonio. Woyte et al. (2007) used wavelet-based spectral analysis, which decomposes instantaneous k_t into orthonormal signals. It is also worth highlighting the studies by Tomson et al. (2008) describing the distribution of ramp magnitudes for five-minute average solar irradiance, and Hansen et al. (2010) on the proposal of several statistical criteria for characterizing one-minute average solar irradiance time series. Tovar et al. (1998); Fernández-Peruchena et al. (2010) analyzed one-minute distributions of k_t conditioned to the optical air mass m (relative thickness of the air path traversed by a Sun's ray to reach the Earth's surface), conditioned to hourly k_t (k_{th}) (Tovar et al., 2001; Fernández-Peruchena et al., 2010), and conditioned to both m and k_{th} (Fernández-Peruchena et al., 2010) (results derived at a single location). Finally, Lave et al. (2012) computed clear-sky indices at one-second resolution to estimate the smoothing of aggregated power output due to geographic dispersion in a distribution feeder.

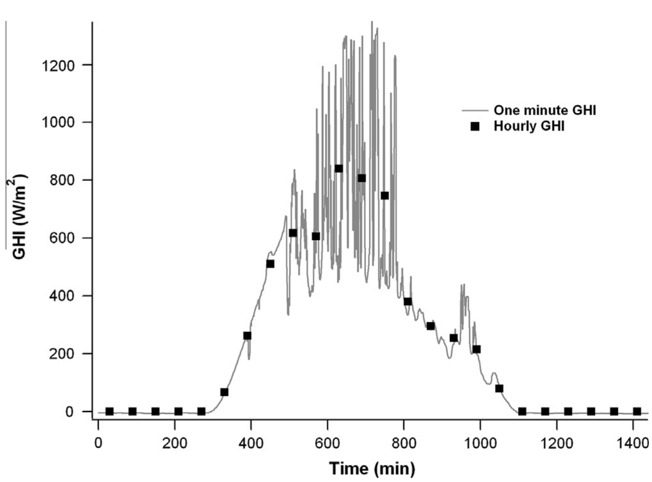

Fig. 1. One-minute GHI records and the corresponding hourly values. Source: Carpentras BSRN radiometric station.

In this study, one-minute GHI data have been analyzed at various locations and climates as a function of m and k_{th} in which they are included. This analysis allows the evaluation of the influence of local atmospheric conditions in high-frequency solar irradiance series, and in turn, facilitates the characterization of short-term variability of solar irradiance as a function of the corresponding hourly data in which they are included (Perez et al., 2011).

2. Materials and methods

2.1. Experimental setup

We used surface radiation measurements from nine stations belonging to the Baseline Surface Radiation Network (BSRN), a project of the World Climate Research Program (WCRP) that aims to measure surface radiative fluxes at the highest possible accuracy with well-calibrated state-of-the-art instrumentation at selected sites in the major climate zones (Ohmura et al., 1998). BSRN data underwent rigorous quality checks (Ohmura et al., 1998; Gilgen and Ohmura, 1999), to assure high accuracy as well as homogeneity in the data.

To carry out this study, we chose radiometric stations representative of the main Köppen classification climate types (Peel et al., 2007), as shown in Table 1. Measurement periods selected correspond to three consecutive years for each station, which include a wide range of conditions representative of each location, including composition of cloud types, the occurrence of differential aerosol loading and ranges of atmospheric humidity, and different seasonal conditions among others. The BSRN radiation variables